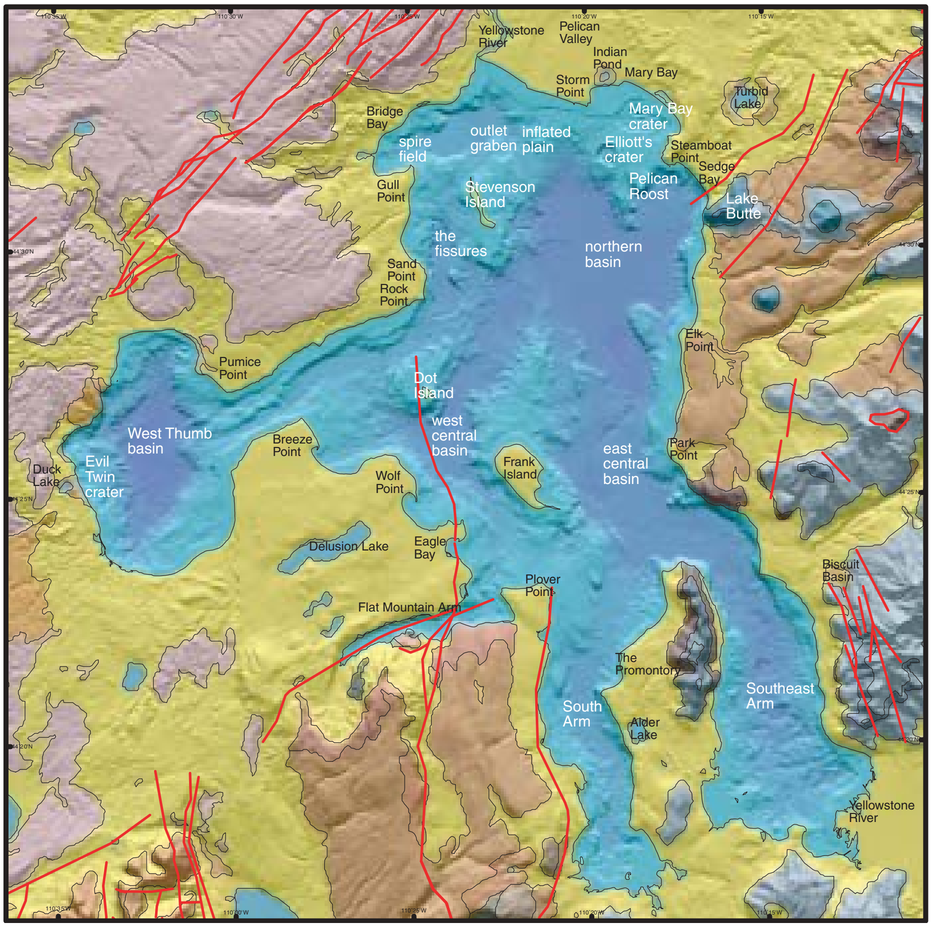
Yellowstone Science

A quarterly publication devoted to the natural and cultural resources



The *YS* Interview: Lisa Morgan

Mapping Yellowstone Lake

Predator and Prey at Fishing Bridge

Volume 11 Number 2

“In War or in Peace”

Now, as these words are written, with prospects of a third world war looming up, with the need all the greater for a haven from the tensions of modern life, for an environment of quiet and peace and serenity, a book like Tilden's leads people's thoughts into channels upon which proper mental balance and perhaps even national sanity may depend. So much the more important, therefore, to cherish these crown jewels among the lands of the nation, to keep them unsullied and intact, to conserve them, not for commercial use of their resources but because of their value in ministering to the human mind and spirit. In war or in peace the national parks have their proper and proportionate place in the life of America. These lands are less than one percent of our area. Surely we are not so poor that we need to destroy them, or so rich that we can afford to lose them.

As Director of the National Park Service from 1940–1951, Newton B. Drury spent a great deal of his tenure fending off a constant flow of demands that the national parks be plundered for the resources they could contribute to wartime and post-war necessity. In that last year of his directorship, in the midst of the Korean War and a growing with the Cold War, he penned these words as an introduction to Freeman Tilden’s *The National Parks: What They Mean to You and Me.*

Yellowstone Lake.

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Volume 11 Number 2 Spring 2003

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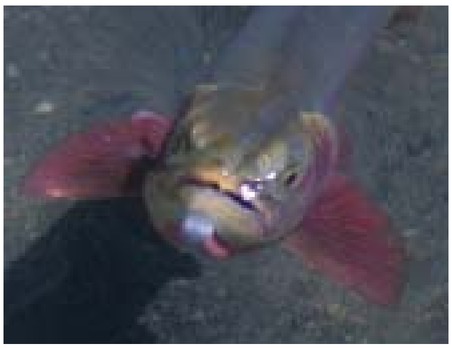

PAUL SCHULLERY

Special Color Issue!

Cover: New high-resolution bathymetric relief map of Yellowstone Lake, acquired by multibeam sonar imaging and seismic mapping, surrounded by colored geologic map of the area around Yellowstone Lake. Courtesy USGS.

Left: 1883 woodblock engraving of Yellowstone Lake, probably produced for publication purposes and handcolored at a later time.

Above: A trout rises to the surface of the Yellowstone River.

Yellowstone Science is published quarterly. Submissions are welcome from all investigators conducting formal research in the Yellowstone area. To submit proposals for articles, to subscribe to *Yellowstone Science*, or to send a letter to the editor, please write to the following address: Editor, *Yellowstone Science*, P.O. Box 168, Yellowstone National Park, WY 82190. You may also email: Roger_J_Anderson@nps.gov.

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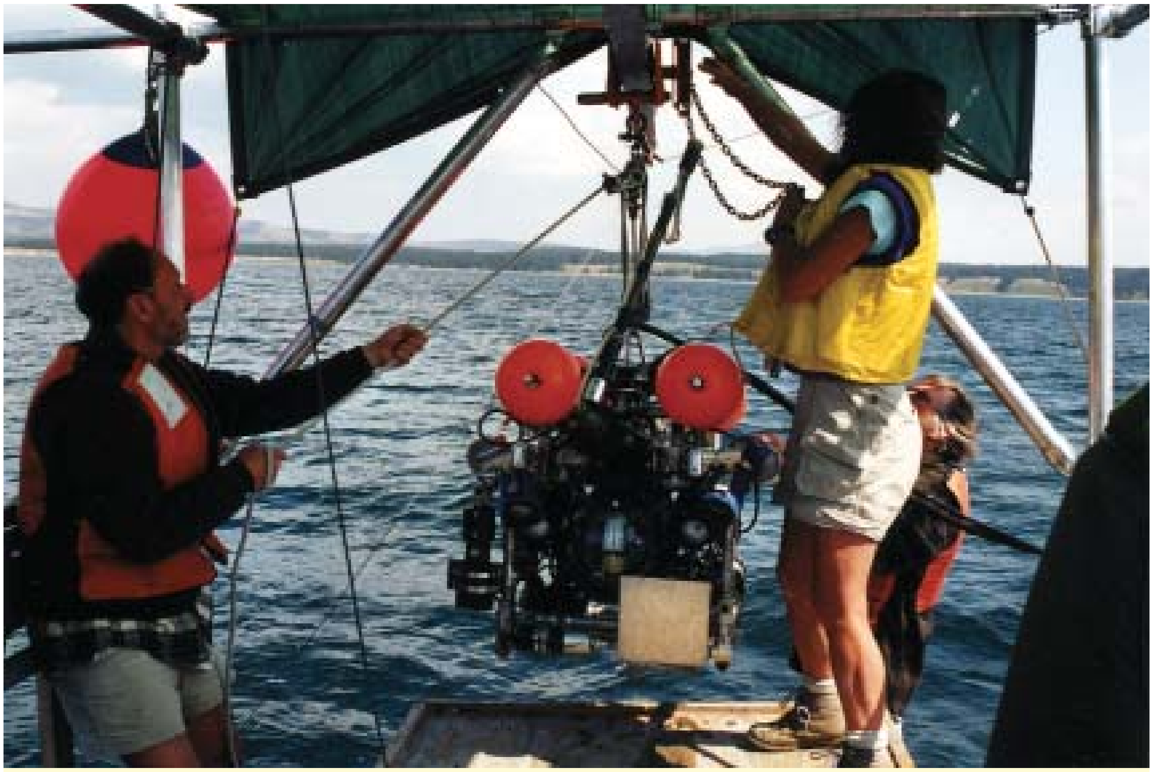
Science with ‘Eyes Wide Open’

An interview with geologist Lisa Morgan

ALICE WONDRAK



Dave Lovalvo, Lisa Morgan, and Pat Shanks launch a remotely-operated vehicle (ROV) into Yellowstone Lake. The ROV aids in ground-truthing recent bathymetric and aeromagnetic mapping of the lake floor conducted by the USGS.

A research geologist with the U.S. Geological Survey, Dr. Lisa Morgan has devoted 23 years to studying the geology and geophysics of volcanic terrains. Since 1999, she has been working in Yellowstone, mapping and interpreting the floor of Yellowstone Lake and its associated potential geologic hazards—an undertaking that was completed last summer. We felt that an achievement of this magnitude warranted extensive coverage in* Yellowstone Science*, and are excited to publish its results. In 2002,* YS *editor Roger Anderson had the opportunity to discuss this project and other issues with Lisa at her Boulder, Colorado, home. We are pleased to include this interview, which provides interesting insights into the mapping process as well as into her personal approach to the science of geology.

YS (Yellowstone Science): Lisa, when we first met, you described your background as a little bit different than that of most geologists, in that you started out as a fine arts major. Could you tell us a little bit more about that, and how it affects how you go about looking at your work today?

LM (Lisa Morgan): I did start out as a fine arts major. Along the way, I took a mineralogy and optical crystallography course in my pursuit of fine arts because I knew we'd be studying color and light theory, which I always thought was pretty interesting. My hope was that the course would enable me to have a better understanding of the color spectrum and how light works. So I took that class and had to take prerequisites in physical and historical geology and before I knew it, I was kind of hooked into geology. And I love geology. One of the things I think fine arts brings to geology is the ability or interest to look in detail at things, and to see things that you might not normally look for. Like when you're drawing, how you're going to draw something is going to be very different than if you just took a photograph of it, and you're going to consider the relationships somewhat differently when you're drawing something than if you're just going to document it with a photograph. So I think fine arts brings this ability to see or look.

I guess I would describe myself as a field geologist who studies the geology and geophysical characteristics of volcanic terrains, and I think having a fine arts perspective gives me another set of tools with which to understand the Earth. My approach is to do science "with eyes wide open." And that's where I see the connection with art, because when you take on a canvas, you start with a specific drawing or painting in mind but as you work on it, the painting begins to shape itself. You don't start a painting saying, "I know exactly what colors I'm going to use. I know exactly what I'm going to draw or paint here." You don't know exactly what the final results will be. And I think you shouldn't, either, with science. When you start out on a proposal, certainly you have ideas of what you want to look at, how to proceed, certain goals, objectives; but you need to make sure that you keep your options open enough so that you don't miss anything that might be necessary in your final interpretation of what you've seen, or what you've recorded. So I think a lot of our work in Yellowstone Lake has been a perfect example of going into an area using techniques we really hadn't used before, using a broad group of different individuals from different disciplines all bringing different skills to the same table, allowing us to identify things we didn't know were there. And allowing us to come to conclusions that we did not know we were going to come to when we started the original study.

YS: Right. So if you had a pre-set paradigm, and you found something else and it didn't fit into that, you don't go with the preconceived notion of what you're going to find. That's what you mean, "eyes wide open."

LM: Exactly. And a lot of times, you'll find, in science, and maybe in other things, too, people want preferred outcomes. They already know where they're going to get to, and they have their product that they're supposed to produce, and that's what they're going to do. And I think it's important that we get out our products that we promised we'll get out, but I think it's also important, as natural scientists, to make sure we're not missing something. So while I have models in mind, I get really frustrated when I'm in the field and somebody tells me, "well, this model tells me it can't be this." I don't care what your model tells you. Just look at the relationship. Forget any model, and just look at that, study what you're seeing in that relationship, and then see how that compares with your model. But sometimes, people go in there saying "well, it's got to be something other than this."

COURTESY LISA MORGAN

Lisa points out a "twig mold" in the 0.64-Ma Lava Creek Tuff. A modern twig has been placed above "twig mold" for comparison purposes.

YS: Is your approach unusual, do you think, among scientists?

LM: I don't know; probably not. I think there are a lot who don't come to the table already working within a prescribed model. But I'm sure there'd be people who would disagree with me on that, too. In my experience, when I meet with people in the field and we're looking at different things, some people already have kind of an idea what it has to be. But I think it's okay to say "well, I don't know what it is." I think nature is a continual puzzle for most of us. And there are a lot of things we still don't know or understand, which keeps us going.

A great example from our 2001 fieldwork is, we discovered charcoal and tree molds in the Lava Creek Tuff. We have actual pieces of charcoal present in some of the tree molds, which was surprising because these pyroclastic flows are typically erupted from very large calderas at pretty incredible speeds, and emplaced at very high temperatures, probably on the order of 800-850ºC.

YS: And it's unusual, because in that heat you would expect everything would be consumed.

LM: That's correct. At this location, we were close to an area interpreted as an eruptive vent for the Yellowstone caldera, and there's a lot of evidence to suggest that there may have been some water involved in this particular part of the emplacement of the deposit, which probably decreased the temperature.

Tree molds are common in basaltic lava flows, such as those in Hawaii and at Craters of the Moon, Idaho, but very little study has been done on the preservation of tree molds in rhyolite pyroclastic flow deposits, like the Lava Creek Tuff. Tree molds and charcoal are somewhat rare occurrences in these types of environments. To find charcoal in this deposit, preserved charcoal, is an interesting discovery, and contributes to what we know about the climate 640,000 years ago when the Yellowstone caldera erupted.

YS: Where in the park did you find this?

LM: It's in the vicinity of Fern Lake, close to the topographic edge of the caldera.

YS: Now, if I was out with you last summer on the trail, walking through that part of Yellowstone, what would you see that I wouldn't necessarily see that would make you want to stop and take a closer look? What are you seeing in the landscape that makes you want to investigate this particular spot, and then how do you, in all of Yellowstone, get to that place and make that kind of find?

LM: Here's exactly what happened. It had been raining on and off that day. Pat Shanks and I were in one work group and Steve Harlan, Lydia Sanz, and Beth Erland were in another work group, and Pat and I were discussing where to go next. It was starting to rain again, and we had to cross the creek. I had taken my backpack off and was putting my raingear on. I'm constantly, just always looking at everything. And as I was tying my shoelaces, I put my eyes on this little piece, that was just a surface piece, probably no more than a couple centimeters long. It had a very fine rim, or coating of silica on it, and then inside of that was this twig impression—this tree mold. And it was very, very tiny. So it was a fluke. Just like a lot of things in science.

And so I saw that little thing, but then it started pouring. And so we skedaddled. We only had the next day left, and I just had this feeling that I had to go back to this site and have a closer look at the impression and site in general. Anyway, we went back up there, and I said, "look at this. It is a tree mold." And I just happened to pick this piece up, and there was all this charcoal, and also pine needles and impressions.

And Pat said, "well maybe that got in there through some kind of later fluvial action, or maybe there was just natural plating for some reason, and you had some flooding, and you got the pine needles in there," and so then I went to another, and I said, "what appears as the characteristic feature of this particular site and deposit is the unusual nature of the platyness of the unit and that's a reflection of its content of organic matter." I said to Pat, "I think the platyness and the organic matter in the ignimibrite are part of the original deposit. I'll bet you a beer that when I go over to that platy zone and that platy zone and that one and all of these zones will be full of charcoal and have impressions of pine needles." He said ok to the bet. So I went and looked at all these different places in the rock exposure, and each one was full of charcoal and pine needle impressions. So Pat ended up buying me a beer after our 13-mile trek out of the backcountry. But you see, the beauty of having people work with you with different backgrounds, is that everyone brings a somewhat different perspective and set of experiences. It's much better than just having your own ideas and self to bounce concepts off. It's always good to have somebody who will challenge one's thinking. It keeps you honest and keeps you thinking.

I guess one of the things our project has exemplified is that not any one person has all the answers.

Later, when I told Ken Pierce [of the USGS] about the tree molds and pine needle impressions found in the Lava Creek Tuff, his reaction was, "Oh my gosh! That is so cool," because in the field of paleoclimatology, a debate exists about whether the Yellowstone caldera erupted during a glacial or interglacial period. And he said, "I think you've got key evidence now for showing the Yellowstone caldera erupted during an interglacial period. It has to be, to have all those pine needles and trees." So that was kind of cool.

YS: It's amazing. Without that collaboration, without people looking at the resource from different perspectives, you might not have made that really critical connection.

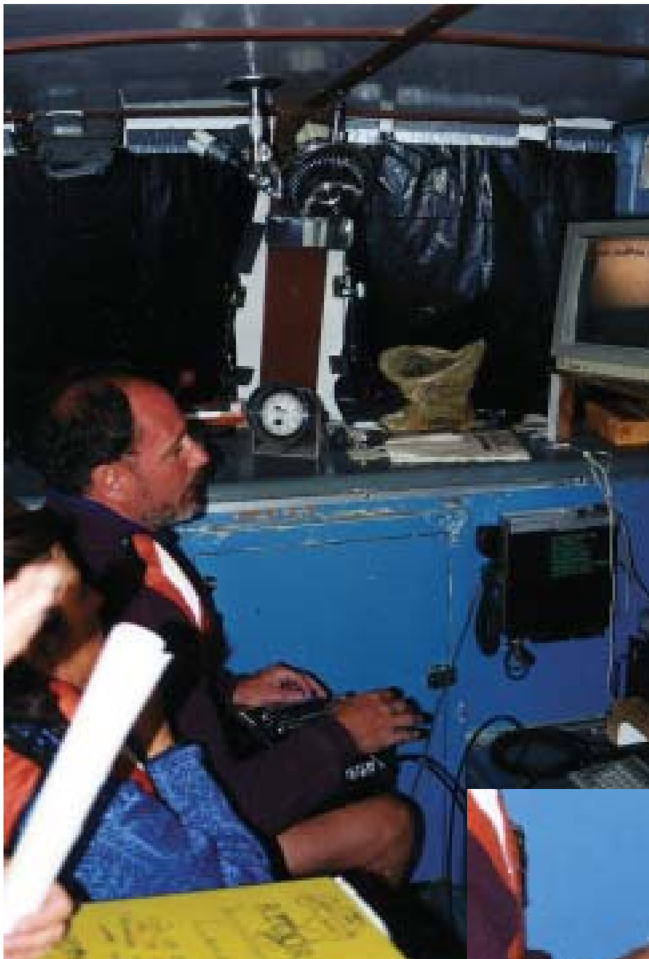
LM: That's right. So anyway, back to the eyes wide open, that allowed us to see that. A lot of the discoveries on Yellowstone Lake have happened the same way. Before we started our West Thumb survey, the current thinking was that most features in the lake are from the last glacial period since it's pretty well established that over a kilometer of ice was over the lake 20,000 years ago. That certainly had to have had a pretty profound influence in shaping the lake. But what we've found is that it certainly is not the only, nor was it the most important, influence on shaping the floor of the lake.

People had previously mapped Stevenson, Frank, and Dot Islands as being glacial remnants. And, certainly, if you went out there today, the rocks exposed on the islands are glacial tills. But what we've found with our high-resolution, aeromagnetic map, (based on the magnetic survey done with an airplane), in tandem with our sonar and seismic surveys of the lake, was

PAT SHANKS

Lisa Morgan and fellow USGS geologist Ken Pierce kick back on the Mary Bay explosion breccia deposit.

ALICE WONDRAK



Dave Lovalvo at the controls of the ROV he designed and built. What the ROV sees is visible on the computer monitor seen at the far right. A second monitor (not seen) displays water temperature readings and a second picture of the lake floor. This photo was taken inside the cabin of the NPS's *Cutthroat,* which is dedicated for research purposes.

ALICE WONDRAK

that the majority of the underwater topography, or the bathymetry of the lake, is really due to rhyolitic lava flows that were emplaced some time after the Yellowstone caldera formed. Now, in retrospect, I think, "Oh, well, that's so obvious," because what do you see around there? It's all lava flows. And why would you think that all of a sudden, just because you have a lake, the lava flows wouldn't be in there? But it was a big, major discovery in mapping West Thumb.

We've found that discontinuities, or anomalies, on the aeromagnetic map coincide with the mapped extent of the rhyolitic lava flows on land, and you can follow those out into the lake. Our detailed new bathymetric maps of the lake floor show that many of the magnetic anomalies coincide with hummocky areas of high relief. We interpret these as rhyolitic lava flows, and suggest that Frank, Dot, and Stevenson Islands are on these large lava flows. So the glacial tills that occur on Dot, Frank, and Stevenson Islands are really just mantling much larger features; rhyolite lava flows underlie the islands and shape the lake bottom. And if we had held on to the old model, we may have been blind to seeing that those flows were there.

YS: Explain to the uninitiated about these aeromagnetic maps you're talking about. What's the process, and what does it generate?

LM: Basically, we attach a magnetometer onto a fixed-wing airplane, and then this airplane flies over the topography at a constant elevation above the terrain. In this particular survey, the plane flew lines 400 meters apart on an east-west orientation, in a continuous pattern over the park. The magnetometer measures the total magnetic intensity of the Earth's field, and that can be broken down into two main components, the magnetic remanence and magnetic susceptibility. Generally, the magnetic remanence records the signature from the earth's magnetic field that the rock acquired at the time of its formation.

Volcanic rocks are emplaced at temperatures above the Curie temperature, which refers to the temperature below which a mineral of a specific composition becomes magnetic. Minerals in the volcanic deposit acquire the magnetization of the Earth's field at the time that that rock was emplaced and give the rock its specific magnetic remanence direction. The earth's magnetic field changes its polarity over time so that volcanic rocks erupted at different times will have different and specific magnetic remanence directions. With magnetic intensity, we also measure the magnetic susceptibility, which is basically a measurement of how susceptible that rock is to an ambient magnetic field.

Susceptibility values can vary depending on a range of conditions. In the case of Yellowstone, what seems to be the major variable for susceptibility is how hydrothermally-altered those rocks are. When your rock is extremely hydrothermally altered, the magnetic minerals in that rock are also altered, and become much less magnetic. A lot of times what we're seeing is titanomagnetites going to hematite or ilmenite. Hematite is nonmagnetic and ilmenite is weakly magnetic, so the magnetic susceptibility of the rock goes to almost nothing. Most of the rocks we're looking at in much of the Yellowstone Lake area were erupted in the last 700,000 years, after the last big reversal in the Earth's magnetic field. So when we're looking at the total magnetic intensity of the rocks in Yellowstone Lake, the variable that is changing most is the magnetic susceptibility, which in this case reflects the amount of hydrothermal alteration in the rock.

In many places in Yellowstone, hydrothermal alteration is associated with thermal springs. Hot waters come up along conduits and alter the rock and magnetic minerals through which they're flowing. The hydrothermal alteration of the rock lowers the magnetic susceptibility. When you look at the newly acquired total magnetic intensity map of Yellowstone, you see a map that has areas with magnetic highs and areas with magnetic lows. In some areas, we can use this map as a guide for where we might expect hydrothermal alteration to be present; in other areas, we can use the map to identify faults and other structures.

ALICE WONDRAK

Remotely-operated vehicle (ROV). The large orange balls are flotation units. Water samples are drawn through the large tube mounted on the left. A thermometer/camera is visible in the mid-foreground, directly above the basket used for scooping up sediment samples from the lake floor.

YS: So this is how you go about looking at the park, and looking at the rocks, and trying to piece together all of the stories that they have to tell?

LM: I guess one of the things our project really has exemplified is that not any one person has all the answers. I think if we went into Yellowstone Lake just doing a bathymetric map, we'd have a pretty appealing map, but the bathymetry combined with the total magnetic intensity map and the seismic reflection profiles enable our producing a more powerful product with a higher level of confidence. Add to this the data we collect with the submersible ROV (remotely operated vehicle), and the data set is pretty complete. The ROV is wonderful, because it allows us to groundtruth what we have imaged with the multibeam and seismic sonar systems. The ROV is a one-meter-by-one-and-a-half meter vehicle, built and piloted by Dave Lovalvo of Eastern Oceanics. It's attached to the boat by a 200-meter tether, which allows continuous observation of the lake floor. At its front is a pan-and-tilt video camera, which records images from the floor of the lake. On the front is also mounted a 35-mm camera. The video camera is on at all times so we can really see the floor of the lake. That aids us in our sampling, and the still lifes are wonderful to see. The ROV is great also because it's able to measure temperatures and collect solid and fluid samples of hydrothermal vents, lake water, and sinter. Later these can be taken to the laboratory and be analyzed for mineralogy, chemical and isotopic composition, and microscopic structures.

So the ROV allows us to observe and sample what we have imaged bathymetrically and seismically. And that's been critical. The multi-beam mapping of Yellowstone Lake presented challenges seldom found elsewhere. Thermal vents so dominant in different parts of the lake cause frequent changes in the temperature structure of the lake, and therefore, the sound velocity profile. In our first year (1999), when we mapped the northern part of the lake, we identified several features, which turned out to be artifacts in the data. So we collected more frequent sound velocity profiles than one would in a non-thermal environment. Having the ROV as our eyes and hands on the bottom of the lake allowed us to confirm the bathymetric images.

While we're very confident of our imaged data, the ability to sample fluids and solids, measure temperatures, and photographically document the lake floor adds an incredibly valuable component to our lake studies. In 2000, we went with the ROV to linear features west of Stevenson Island that were imaged in 1999. As a result, we have photographic evidence that the features are fissures with hot water coming up along open cracks in soft mud and precipitating iron and manganese oxides on the fissure walls. The fissures are parallel to and part of the Eagle Bay fault zone, which is a young fault system mapped south of the lake at Eagle Bay.

This system probably continues northward of the fissures to the young graben north of Stevenson Island.

YS: Does that continue with the fault near the Lake Hotel?

LM: That's right. The Lake Hotel is near the fault. So again, our mapping of the Lake has enabled us to look at its geology in more detail and in a broader context. And Yellowstone Lake isn't an easy lake at all to figure out, or to work on. You think of most lakes as being quiet, calm, and good passive recorders of the local climate and geologic processes. But Yellowstone Lake is anything but quiet.

BETTY SKIPP

Lisa Morgan in 1980, doing field work for her master's degree. She is sitting next to the base of the 6.65 million year old Blacktail Creek Tuff, the oldest caldera-forming ignimbrite from the Heise volcanic field. The Heise volcanic field (4-7 Ma), on the eastern Snake River Plain, is similar in origin to the Yellowstone Plateau volcanic field, and immediately preceded its formation in space and time along the volcanic track of the Yellowstone hot spot.

YS: Which of those technologies—the aeromagnetic survey, the ROV, the bathymetry—played a role in determining the caldera boundary under the water?

LM: I would say the two most important ones were probably the recently acquired aeromagnetic data and the bathymetry. Much discussion has been had about where to draw the caldera boundary through the lake. Using both of these data sets, we trace the topographic margin of the Yellowstone caldera right through Frank Island.

YS: Weren't you going back and forth? You were describing once about how you were out on the boat, and you were taking measurements on what you thought was inside the caldera, outside the caldera.

LM: Yeah. Once we got the bathymetry, it coincided perfectly with where we had put the boundary based on the mag data. And so that was so cool, and then we were able to take the ROV, and we could see the caldera margin in the lake. It looks like a bunch of discontinuous, bathtub-shaped troughs, kind of marching through the central basin. The multiple data sets give the same conclusion, so that one can say with much better confidence that this is definitely where the caldera margin is.

YS: I'm going to just back up for a few minutes, and get us back to how we began the discussion, from the fine arts to geology, to this philosophy of looking at your work with your eyes wide open, and ask you to elaborate a little more about your background. Once you found geology, tell us a bit about your schooling, where you went, your degrees…

LM: I went to the University of Missouri at Kansas City, and at that time it was just a small undergraduate geology department, and I had great mentoring and opportunities there. That was key. I got a job in the department, starting probably in my junior year. I was a lab technician there. After I graduated, I worked for a short time in a jewelry store with the intention of eventually becoming a gemologist, but then I got a job that paid twice as much with an oil company. I stayed with the oil company about 10 months but left to return to the University to teach labs for introductory geology classes and work as a technician in their analytical lab. I then moved to Colorado and got my Master's degree at the University of Colorado at Boulder, focusing on igneous petrology and volcanology.

I then had a great opportunity in 1980 to work at Mt. St. Helens, and on August 7, I witnessed one of its smaller pyroclastic-flow-producing eruptions from a plane about a kilometer or two away from the vent. That eruption was significant because it created quite a good eruptive cloud, and in that cloud you could see part of it collapsing and forming pyroclastic flows on the flanks of the volcano. While the pyroclastic flow was moving, one could see how this flow concentrated in areas of lower topography, such as valleys coming off of St. Helens. I could see fine ash being blown out of the front of the deposit. And I just decided then I wanted to focus on how pyroclastic flows are emplaced. Being at St. Helens gave me a great opportunity to see what volcanologists do. And so in the following year I decided to go for my Ph.D., and study with George P. L. Walker, at the University of Hawaii, whose primary focus at the time was ash deposits, their facies, and emplacement processes.

YS: When did you first work in Yellowstone on geology?

LM: I started coming to Yellowstone probably 1979–1980, because I was working on the Snake River Plain and there were many similarities between the Quaternary rhyolites in Yellowstone and the slightly older rhyolites on the Snake River Plain. I was working on my Master's thesis; its focus was a stratigraphic study of a thick section of pyroclastic flow deposits exposed on the northern margin of the eastern Snake River Plain. As we know now, but didn't know then, the Snake River Plain is a whole bunch of old Yellowstone-like calderas and volcanic fields. I was first formally assigned to Yellowstone in 1995, but, over the previous 15 years, I used the more complete exposures and caldera-related features present in Yellowstone as a way to better understand what I was looking at on the Snake River Plain, where exposures of rhyolites are mostly limited to the margins of the Plain. Today, most Yellowstone-like features in the Snake River Plain are covered by Quaternary or very recent, young basalts. Eventually, like the eastern Snake River Plain, Yellowstone will be much lower in elevation than it is now and also will be covered by basalts.

YS: Explain to me how in the future Yellowstone will be much lower.

LM: Currently scientists can image molten, very hot material underneath Yellowstone, and, in general, this mass of hot material causes the general Yellowstone area to be topographically higher than the surrounding areas. Over time, if the Yellowstone caldera is similar to earlier Quaternary calderas in the Yellowstone Plateau volcanic field, which we have every reason to believe is true, basaltic lavas will erupt, eventually fill the caldera floor, and conceal the Yellowstone caldera. What is now molten magma will eventually crystallize and become denser, and thus less buoyant. The overall topographic elevation will subside from today's current elevation. With continued southwest movement of the North American plate over the thermal disturbance that causes Yellowstone today, an area northeast of the present-day location of the Yellowstone Plateau will become elevated and rise above Yellowstone. In fact, we can already witness this. This process of uplift followed by volcanism has been occurring for the past 16 million years along the Snake River Plain starting in southwest Idaho. So today, Yellowstone is anywhere from 1 to 2 kilometers above the Snake River Plain, depending on where one takes measurements.

ALICE WONDRAK

Ground-truthing with the ROV means visiting several sites each day, requiring that the crew drop and haul anchor numerous times. Here, Lisa displays some hydrothermally-altered clay that came up with the anchor.

YS: When did you begin to work with the USGS?

LM: In 1977, when I moved to Colorado.

YS: What was your first job with them?

LM: It was great. I made a Denver dump map. My job was basically compiling a map showing where all the landfills in the greater Denver area were. And that map transformed a lot of how I live my life today, and how I look at what our responsibilities are as citizens on Earth. The USGS had been asked to do this because there had been a series of accidents associated with former landfills. Some accidents were due to spontaneous combustion of methane that caused some fires, some explosions. I think a couple of people were either seriously burnt or killed. Also, housing developments constructed on top of these landfills were developing cracked foundations and walls due to differential subsidence in the landfills. It was imperative that a comprehensive look be taken at where these landfills were located, so that city and county planners could make more informed choices of where to allow or deny development. I was blown away by how many dumps there were, and what went into these landfills. So much of it could be recycled, reused, and not put in there in the first place. And since then, I'd say starting in like the mid-80s, our family has probably put out no more than maybe three to four bags of garbage in a year.

YS: Really.

LM: *(Smiling)* Yeah. We don't subscribe to the landfill too much; they should be kept to a minimum. There's a berm out in our yard where we put all the inert building material that would have gone to the landfill, but that we took care of here. Right now I'm on the Boulder County Recycling and Composting Authority, and our goal as a county is to divert, by 2005, our solid waste levels from 1994 by 50%. And I think we're going to achieve that goal. In the City of Boulder, our single-family residential diversion rate is at 49%, so we have almost met our 2005 goal several years ahead of schedule. However, in the arenas of commercial and industrial waste and for multi-family units, our diversion rates are only about 15-20% from 1994 levels, so these are areas where we still need to focus and significantly increase our diversion rates. And we're pushing the stakes up higher and trying to get to 80% diversion from 1994 levels. It's an informal goal for the City of Boulder. Last year, the city council passed a new ordinance, referred to as the "pay-as-you-throw" ordinance, that really forced individuals to pay the true cost of their trash. This has resulted in major behavior changes and a significant increase in our level of recycling and reuse. People can do it, but you have to have the infrastructure in place, like curbside pickup and mixed paper and commingled containers. So that's a long story, but that was my first job with the USGS.

YS: What's your current job?

LM: Now I work at Yellowstone. This year I'm assigned to Yellowstone 100% of my time. We've finished the map of Yellowstone Lake, and are working on various aspects of the postglacial hydrothermal explosion craters and deposits that are probably the most immediate serious hazard in the park. The last very large hydrothermal explosion event that we know of was 3,000 years ago at Indian Pond. Of course, in recent years smaller hydrothermal explosion events have occurred in the Norris basin, Biscuit Basin (1915), West Thumb, and Potts thermal basins and elsewhere in the park. So they're very much a current feature of activity that Yellowstone National Park has to deal with. I've also been working on the physical characteristics of the Lava Creek tuff and its emplacement, and how it relates to the formation of the Yellowstone caldera. And then there's the mapping of Yellowstone Lake that's basically consumed me for the past four years.

YS: Was your work in Yellowstone on the caldera what ultimately brought you to do the extensive work on Yellowstone Lake? What intrigued you about Yellowstone Lake that has led you to do so much work there?

LM: Yes, originally I came to Yellowstone to work on the Lava Creek Tuff, which erupted from the Yellowstone caldera, to better understand its formation. But I also came to do the ground-truth for the aeromagnetic survey we flew in 1996. With Steve Harlan, I've collected oriented core-samples from most of the Quaternary and Tertiary volcanic rocks in the park for our magnetic studies.

As far as the lake, if you think of all of the geologic maps in Yellowstone National Park, the one place that didn't have a geologic map was the Lake. What really got me into Yellowstone Lake was my interest in the hydrothermal explosion deposits. We were already engaged in detailed studies of the deposits from Mary Bay, Indian Pond, and Turbid Lake on land, and I was very interested in trying to understand the eruption of Mary Bay. In our 1999 survey, one of our big discoveries was what we are now calling Elliott's crater, which is an 800-meter wide hydrothermal explosion crater complex on the floor of the lake in the northern basin.


ALICE WONDRAK

The sun rises on Yellowstone Lake. The lake's unpredictable summer weather makes it best to get an early start.

YS: The work you and others have done in recent years has really kind of revolutionized the way we look at the lake. If we could look at the bottom of Yellowstone Lake, from the mapping you've done, what would it look like?

LM: If you took all the water out, you would have a very hummocky terrain. You'd have a terrain very similar to what you see in the Central Plateau now, where there are a lot of very steep-sided, hummocky terrain dominated by rhyolitic lava flows. And these lava flows would have a cap of glacial and lacustrine sediments. Intermixed with this hummocky terrain would be a whole series of hydrothermal vent fields throughout the lake. The hydrothermal vents are associated with the lava flows, generally near their edges. And so, one of the largest thermal fields in Yellowstone National Park is on the floor of the lake. It's pretty magical exploring these areas. On top of this very hot area, we've seen a lot of fissures, which are linear cracks in the lake bottom. I can't think of an area on land in Yellowstone where you have big open fissures like these. Maybe in some of the thermal fields, but some of the lake-bottom fissures that were discovered in 1999 and 2001, in the northern and central lake, extend for several kilometers. Another feature one would see are the very large lake-bottom explosion craters, similar to Turbid Lake and Indian Pond on land.

YS: Duck Lake, too?

LM: Yes, Duck Lake is a large explosion crater immediately west of West

Thumb basin. You may have noticed a steep slope west of the West Thumb Geyser Basin. This is an apron of debris that was ejected during the hydrothermal explosion of Duck Lake. A morphological difference between the large explosion craters on land and those on the floor of the lake is the radial apron of debris around the craters we see on land. In the lake, a well-defined rim around the central crater is absent. Most of this difference may have to do with the medium in which the eruption occurred.

YS: And the vents, and the spires…

LM: And then you'd have spires, or conical features, that are anywhere from one meter all the way up to about 8 meters high, over in Bridge Bay. We think Monument Geyser Basin, near the northwestern edge of the Yellowstone caldera, may be analogous in its origin to Bridge Bay. And then just north of Stevenson Island, you'd also see a large young graben, which is a down-dropped block with bounding faults. About two meters of displacement is on the west side, and about six meters of displacement on the east side. And we found a lot more vents in West Thumb basin than we had previously thought.

YS: Where else did you find them?

LM: They're in the south-central part of the West Thumb basin as well as in the northern part of the basin, along the edges of rhyolitic lava flows.

YS: How about Mary Bay?

LM: Mary Bay is a huge crater complex. It's a whole series of smaller craters inside a much larger main crater. One of the things that we need to get a better handle on is that not all of these craters are produced by explosions. We think some of these craters may also be produced by dissolution collapse. As you know, the lake has areas of very high heat flow, which came out of research by previous workers such as Paul Morgan, Bob Smith, and Dave Blackwell. The high heat flow is responsible for the occurrence of hundreds of hot springs on the lake floor. The hydrothermal fluids are very acidic and change the composition of the rocks around them. And so in the lake, most of the rock composition originally was rhyolite, which is mostly quartz, silica, feldspar, and plagioclase. Feldspars and plagioclase are altered easily by this acidic fluid and are changed into clays. And then these hydrothermal minerals precipitate in this system forming a kind of impermeable seal. At some point all the vents and fissures that were conduits for these fluids seal up. The acidic hydrothermal fluids and gases continue to do their work, which is to alter the substrata, and at some time, either these things explode and there's a catastrophic failure of that sealant, or there's collapse of all this material underneath. Now, I don't think we understand how we distinguish these two at this point, or how we can forecast what's going to happen. But I certainly hope some of our seismic profiles give us more insight into our ability to look at the structural integri-

ALICE WONDRAK

"We got bubbles!" Although GPS units are the crew's primary mode of navigation, patches of bubbles rising to the lake's surface can act as hydrothermal landmarks as those aboard the *Cutthroat* search for the exact spot to launch the ROV.

ty of the rocks underneath the lake. Or the lake sediments.

YS: Of all the findings you've made on the lake, what surprised you the most, would you say?

LM: I don't know, I mean, the whole thing has been like a discovery a day. And so it's been really exciting, and has opened new ways to examine multiple active processes, and has been quite fun along the way. You never are quite sure what you're going to find. I guess I'd say the biggest surprise was either the fact that the rhyolitic lava flows played such an important role in shaping the floor of the lake and controlling the location of the hydrothermal vents, or that the caldera margin showed up so clearly in the bathymetry and coincided with areas of magnetic lows. That was really cool.

To see the caldera margin is really fascinating. And the hydrothermal craters are just phenomenal. When you see these large structures, you know a very complex process is involved, because not only do you have 800- to 2000-meter diameter structures, but throughout the floor of these structures hydrothermal processes are active and one can see and sample active hydrothermal vents. And so you think "well, where can you go on land where you could see something like that?" and so in the summer of 2001, we started mapping Indian Pond and Duck Lake, and right now we only have the seismic reflection profiles. But that should give us a lot of indication of what's going on in those lakes. I think it's important for the park, from a public safety perspective, to understand activity occurring in the hydrothermal explosion crater lakes as well, because like geology, nothing's static. We know from our reconnaissance seismic surveys in Duck Lake and Indian Pond that active hydrothermal vents are on their floors.

Also, large landslide deposits, including a couple large detachment blocks, have come off the eastern, and to a lesser extent, western shores of Yellowstone Lake. These are kind of hummocky, but not as pronounced as the lava flows. The causes of these landslides and their effects on Yellowstone Lake are an important topic for further study.

YS: How much of the lake bottom has been surveyed?

COURTESY LISA MORGAN

Even graduate students need a break every now and then.

LM: We finished surveying the South and Southeast Arms in 2002, so the bathymetric mapping of the lake is completed! About 75–80% of the lake is within the Yellowstone caldera. Outside the caldera are the South and Southeast Arms, which are fault-bounded valleys whose shape has been enhanced significantly by glacial processes. Much of the floor of the Southeast Arm is characterized with a hummocky bathymetry with many depressions reflective of kettle and glacial meltwater terrain seen elsewhere in Yellowstone and Grand Teton National Parks. After melting, voids left by the ice were later partially filled with slumped sediment leaving large, tens of meters wide, irregularly-shaped depressions.

YS: Earlier, you talked a little bit about the interplay between geology and biology. Could you elaborate?

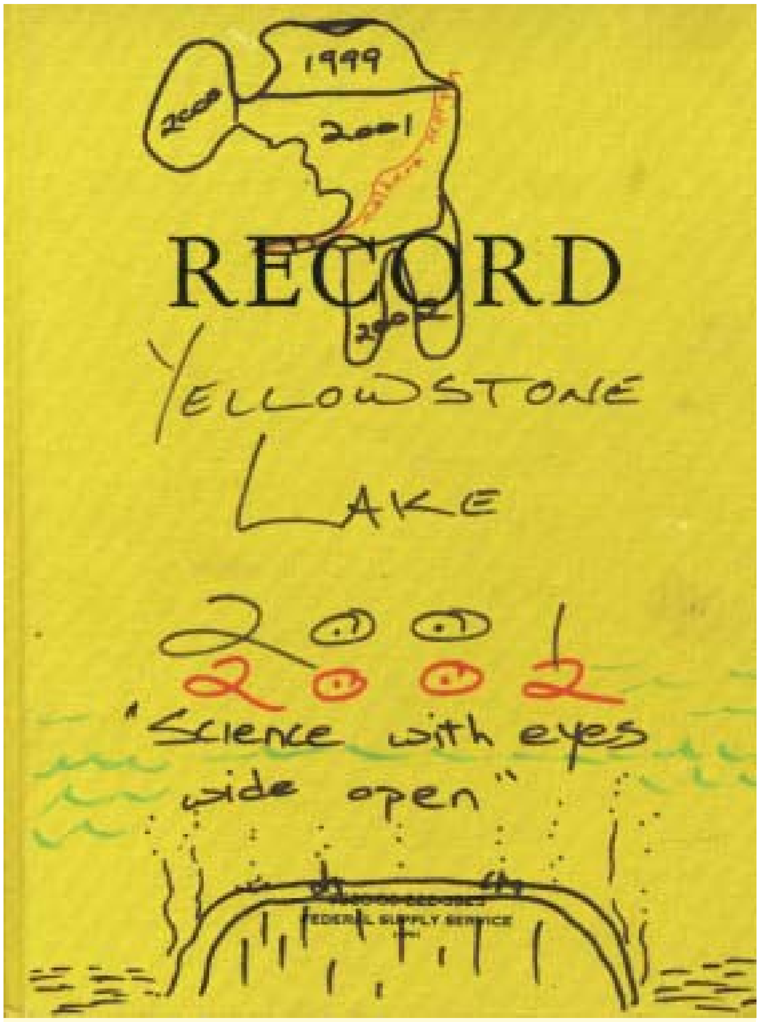
LM: As you know, lake trout have been discovered in Yellowstone Lake, and the native cutthroat trout is prey to the lake trout. Pat Shanks has been working on the geochemistry of the sublacustrine hydrothermal fluids, looking at toxic elements that we know exist in other hydrothermal systems, including mercury, antimony, and thallium. Crustaceans are a primary food source for cutthroat trout, so the question arose, what kind of transmission is there from the vents to the lowest life forms that we could identify, on up through the food chain to the cutthroat trout and up to the lake trout? So he started looking at mercury content of fish muscle, vital organs, and skin. And he found a higher than normal concentration in both the lake and cutthroat trout.

The park is interested in identifying areas in the lake where lake trout spawn. Lake trout are anadromous, meaning they stay within the lake their entire lives. Cutthroat are potomodromous meaning they spawn in the streams that feed into the lake during the early summer and later they come back and live in the lake. When they are spawning in the streams, they become potential food sources for many species, some threatened or endangered such as grizzly bears, bald eagles, otters, and osprey. If the cutthroat disappeared, the lake trout, which never leave the lake, would not take their place in the ecosystem. It's a major resource issue for the park and understanding where lake trout spawn is key to controlling their numbers and to the ultimate survival of the cutthroat trout.

Our understanding when we started this study is that lake trout like to spawn in gravelly areas. So we thought if we could identify gravelly areas in the lake with high-resolution bathymetry and seismic profiles, we could lead the biologists to the spawning areas for the lake trout. As it turns out, we're finding that the lake trout hang out in other areas in addition to the deep gravelly areas. The cutthroat trout like to hang out in warm, thermal shallow areas, which have been called "cutthroat jacuzzis." The Park Service has found lake trout coming into some of these jacuzzi vent areas to prey on the cutthroat trout.

So biology has a major role in the Yellowstone Lake studies. For one, identifying what effects toxic metals present in hydrothermal fluids have on lake water chemistry and how they affect its ecosystem is important. Secondly, how those effects are rippled up into the larger animals outside the lake is equally important. Chuck Schwartz, Charles Robbins, and the Interagency Grizzly Bear Study Team working with Bob Rye and Pat Shanks recently have analyzed hair from four bears in the park. Two of those bears come from areas very close to the lake, two are from farther away. The two bears close to the lake have elevated levels of mercury in their hair whereas those bears not living near the lake do not. So in this example, it seems a strong relationship exists between the geology of the lake and grizzly bear and cutthroat trout ecology.

That's one issue. Another is the spires and how they formed. Scanning electron microscopic (SEM) images show that the spires are composed of a variety of diatoms and silicified bacteria. And that was a big surprise. We had supposed that the hot silica-enriched waters hitting the cold lake water interface would precipitate amorphous silica without biologic involvement. When we went and looked at the spires under the SEM, sure enough, our compositions were for pure silica but the material was primarily silicified bacteria with diatoms. And so there's something happening on the floor of the lake that is very much involved in some of the very basic life forms that operate very closely with development of these hydrothermal vents. So it's kind of interesting to see the full circle come back.



Lisa Morgan's field notebook.

YS: What work remains to be done? What questions still need to be asked when you look at the lake?

LM: Well, for starters, I think the lake, the park, and science would be well served by doing a series of cores on selected sites in the lake. That would shed a lot of information about the timing of different events: timing of seismic events, of hydrothermal explosion events, of landslides. Cores collected in specific areas would give information about what triggers the landslides. Were they triggered seismically, or were they triggered from the hydrothermal explosion events? Or from something else? Potentially, data from selected cores could tell us something about evolution of the different hydrothermal systems. Not just the hydrothermal vents, but also the large hydrothermal explosion complexes. I would also like to know more about the climate of Yellowstone in the last 12,000 years. Certainly, coring into the lake would give us a clearer idea of what the climate was like during these different events, and what kind of influences there might have been.

We need to have a better understanding of the issue between large-scale collapse of hydrothermally altered features versus large-scale hydrothermal explosions and associated hazards. We need to improve our understanding of doming activity on the lake floor. Do these doming events always end up in an explosion, or do they end up in a collapse, or do some of them not do anything? I think that's important. Are the domes that have been identified in our surveys potential precursors to hydrothermal explosions? If so, how do we monitor these features? Also the young and active graben north of Stevenson Island should be monitored, especially given this structure's proximity to the Lake Hotel. Putting CO_2

and SO_2 sensors next to vents in the domes is important. I would like to see more work done using LIDAR (light detection and ranging) outside the lake. Ken Pierce and Ray Watts's initial work with this technique in association with some other people shows that Storm Point may actually be an inflated structure. And so we might want to examine that pretty closely. Much work remains and, to summarize, this would include mapping, coring and associated studies, assessing the potential hazards, and identifying the instrumentation needed for monitoring.

YS: How about in the broader context of the caldera outside the lake?

LM: Well, I would hope that we get a better understanding of the hydrothermal explosion potential inside the caldera. Most, if not all of the hydrothermal explosions that we've identified occur inside the caldera. So that needs to be assessed. I think it's also very important to understand the "heavy breathing" aspect of the Yellowstone caldera. And again, Ken Pierce has shown a lot of interesting data that looks at the coincidence between uplift and subsidence of the Yellowstone caldera with relationship to timing of some of these hydrothermal explosion events. So I think that's very important. From my perspective, probably one of the greatest and most likely potential hazards in the park is the potential for a hydrothermal explosion. In terms of scale, it's not going to affect North America, but it potentially could affect the park's facilities, infrastructure, and visitors. And when you think of the transient population that goes through Yellowstone on a daily basis, it's very much an urban population. If you took the number of visitors that you have coming to Yellowstone on an annual basis and divided it by the days, you basically have the city of Boulder, Colorado in Yellowstone every day. The problem with your population is it's moving all the time. But the park pretty much controls where it moves. And so it's important that the park have a better understanding of where these hazards may occur.

Clearly, assessment of other potential hazards, such as volcanic and seismic events, are big items and will be included in the ongoing hazard assessment conducted under the auspices of the recently established Yellowstone Volcano Observatory, a joint effort between the USGS, the University of Utah, and the National Park Service (Yellowstone National Park).

A lot of work remains that will continue to build on previous investigators' research and findings. We still have a far way to go in improving our understanding of the connections between geology and biology, and how the biota react to different geologic events in the park.

LISA MORGAN

Yellowstone Lake.

YS: Finally, please describe some of your memorable moments working in the park.

LM: It's been a challenging and rewarding research experience to work in Yellowstone. It's been so much fun to work in Yellowstone. And it's just been kind of a dream, like the summer when we did our backpacking trip up to Fern Lake, it was like, "I can't handle any more discoveries!" *(Laughing)* Just the number of discoveries we've been able to make through the course of our research has been phenomenal, so I feel very lucky to have had this opportunity. It's also been pretty awesome to work in this environment where the sight of a grizzly makes one realize what a unique, special, and still wild place Yellowstone is. To understand the geologic framework in which bears and other species inhabit allows us a more comprehensive understanding of why certain species live where they do and the challenges they face in their environments in order to survive and what we might do to enable their survival. For several of these species, Yellowstone is their last outpost, so it's up to those of us who work in the park to make sure that they're protected. ✪

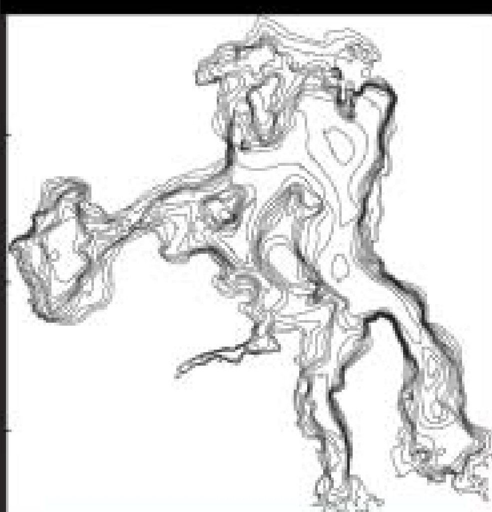
> "The lake was very rough. The waves coming in were equal to waves on the sea coast. Elliott says they were able to take but three soundings, it being rough all the time. The wind once was so strong that the mast was broken off and carried away. The boat rode splendidly."
>
> *Albert Peale, mineralogist, US Geological Survey Hayden survey, August 14, 1871*

Evolution of mapping Yellowstone Lake, 1871-2002

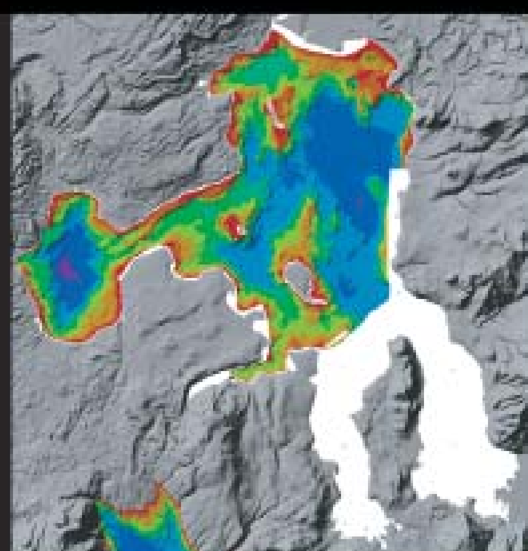
***The* Anna.**

Henry W. Elliott, 1871 Hayden survey

Hague report, 1896



Kaplinski, 1991



U.S. Geological Survey National Park Service 1999-2002

The Floor of Yellowstone Lake is Anything but Quiet!

New Discoveries in Lake Mapping

by Lisa A. Morgan, Pat Shanks, Dave Lovalvo, Kenneth Pierce, Gregory Lee, Michael Webring, William Stephenson, Samuel Johnson, Carol Finn, Boris Schulze, and Stephen Harlan

History of Mapping Yellowstone Lake

Yellowstone Lake is the largest high-altitude lake in North America, with an elevation of 2357 m (7731 feet) and a surface area of 341 km^2 (Plate 1, inset). Over 141 rivers and streams flow into the lake. The Yellowstone River, which enters at the south end of the Southeast Arm, dominates the inflow of water and sediment. The only outlet from the lake is at Fishing Bridge, where the Yellowstone River flows north and discharges 2000–9000 cubic feet/second. The earliest attempt to produce a detailed map of the shoreline and bathymetry of Yellowstone Lake occurred during the 1871 U.S. Geological Survey expedition, when Ferdinand V. Hayden led 28 scientists, scouts, and cooks in a survey of what is now Yellowstone National Park. The sheer effort expended by this group, under the most primitive of working conditions, is impressive on its own, but especially when considered in tandem with the many accomplishments of the survey. A primary goal of the party was "mak(ing) a most thorough survey of [Yellowstone Lake]," reflecting Hayden's general interest in watersheds and river drainage basins.

A 4.5 × 11-foot oak boat with a woolen blanket sail was used to map Yellowstone Lake. Mapping took 24 days and included approximately 300 lead-sink soundings. Navigation was carried out using a prismatic compass. Albert Peale, the survey's mineralogist, described the process in his journal (see box).

The survey mapped a shoreline of 130 miles; the most recently mapped shoreline gives the perimeter of Yellowstone Lake to be 141 miles (227 km). Over 40 soundings were taken along the north and west shores, the deepest being around 300 feet. The survey estimated the deepest part of the lake would be farther east and no deeper than 500 feet. This depth range is comparable to what we know today; the deepest point in Yellowstone Lake is due east of Stevenson Island (Plate 3B) at 131 m (430 feet) deep. In addition, the Hayden survey identified the long NE/SW-trending trough crossing the central basin. Plate 1 shows the map of Yellowstone Lake as drawn by Henry Elliott of the Hayden survey. The map not only shows a detailed topographical sketch of the Yellowstone Lake shoreline but many of the points where soundings were taken for the survey.

A second map of Yellowstone Lake, published in 1896, incorporated elements of the original 1871 Elliott map from the Hayden expedition. While no mention is made in the official USGS report of additional mapping or modifications made to the Elliott Yellowstone Lake map, or even of any additional work on Yellowstone Lake during the years of the Hague survey (1883–89, 1890–91, 1893), the lake was clearly resurveyed and triangulated by H.S. Chase and others, as published in maps in the Hague report and reflected in

> "A man stands on the shore with a compass and takes a bearing to the man in the Boat as he drops the lead, giving a signal at the time. Then the man in the Boat takes a bearing to the fixed point on the shore where the first man is located and thus the soundings will be located on the chart...[Elliott will] make a systematic sketch of the shore with all its indentations [from?] the banks down, indeed, making a complete topographical as well as a pictorial sketch of the shores as seen from the water, for a circuit of at least 130 miles. He will also make soundings, at various points."

Facing page: Plate 1. From top left: (A) Henry Elliott's 1871 map of Yellowstone Lake. The headwaters of the Snake River, Upper Valley of the Yellowstone River, and Pelican River are shown. The area now known as West Thumb is referred to as the South West Arm. (B) W.H. Jackson photo of the survey boat, *The Anna,* with James Stevenson (left) and Chester Dawes on July 28, 1871. (C) 1896 map of Yellowstone Lake and surrounding geology as mapped in the Hague survey. (D) 1992 Kaplinski map. (E) New high-resolution bathymetric map acquired by multibeam sonar imaging and seismic mapping. The area surrounding the lake is shown as a gray-shaded relief map.

Acronyms used in figures

BFZ: Buffalo Fault Zone
EBFZ: Elephant Back Fault Zone
EF: Eagle Bay Fault Zone
HFZ: Hebgen Fault Zone
IP: Indian Pond
LHR: LeHardy Rapids
LV: Lake Village
MB: Mary Bay
PV: Pelican Valley
Qa: Quaternary alluvium (deltaic sediments)
Qg: Quaternary glacial deposits
Qh: Quaternary hydrothermal deposits
Qhe: Quaternary hydrothermal explosion deposits
Ql: Quaternary shallow lake sediments (shallow water deposits and submerged
Qld: Quaternary deep lake sediments (laminated deep-basin deposits)
Qls: Quaternary land slide deposits
Qpca: Quaternary Aster Creek flow
Qpcd: Quaternary Dry Creek flow
Qpce: Quarternary Elephant Back flow
Qpch: Quaternary Hayden Valley flow
Qpcl: Quaternary tuff of Bluff Point
Qpcm: Quaternary Mary Lake flow
Qpcn: Quaternary Nez Perce flow
Qpcp: Quaternary Pitchstone Plateau flow
Qpcw: Quaternary West Thumb flow
Qpcz: Quaternary Pelican Creek flow
Qps: Quaternary tuff of Bluff Point
Qs: Quaternary sediments
Qt: Quaternary talus and slope deposits
Qvl: Quaternary Lava Creek Tuff
Qy: Quaternary Yellowstone Group ignimbrites
SI: Stevenson Island
SP: Sand Point
SPt: Storm Point
TFZ: Teton Fault Zone
Tl: Tertiary Langford Formation volcanics
TL: Turbid Lake
Tli: Tertiary Langford Formation intrusives
Tv: Tertiary volcanic rocks
YR: Yellowstone River

Plate 1. The 1896 map built upon the Elliott map and refined areas on the shoreline, such as in the Delusion Lake area between Flat Mountain Arm and Breeze Point. Where the Elliott map of Yellowstone Lake shows Delusion Lake as an arm of the lake, the Hague map delineates its boundaries and identifies swampy areas nearby. The maps from the Hague survey also include a rather sophisticated geologic map of the subaerial portions of the park around the lake.

The next significant attempt to map Yellowstone Lake came a hundred years later and employed a single-channel echo sounder and a mini-ranger for navigation, requiring interpolation between track lines. Over 1475 km of sonar profiles were collected in 1987, using track lines spaced approximately 500 m apart and connected by 1–2 km-spaced cross lines. An additional 1150 km of sonar profiles were collected in 1988 to fill in data gaps from the 1987 survey. The map identified many thermal areas on the floor of the lake. The resulting bathymetric map has served as the most accurate lake map for Yellowstone National Park for over a decade, and has proven invaluable in addressing serious resource management issues, specifically monitoring and catching the aggressive and piscivorous lake trout.

Ten years after that bathymetric map, development of global positioning technology and high-resolution, multi-beam sonar imaging justified a new, high-resolution mapping effort in the lake. Mapping and sampling conducted in 1999–2002 as a collaborative effort between the USGS, Eastern Oceanics, and the National Park Service utilized state-of-the-art bathymetric, seismic, and submersible remotely-operated vehicle (ROV) equipment to collect data along 200-m track lines with later infill, where necessary. The 1999–2002 mapping of Yellowstone Lake took 62

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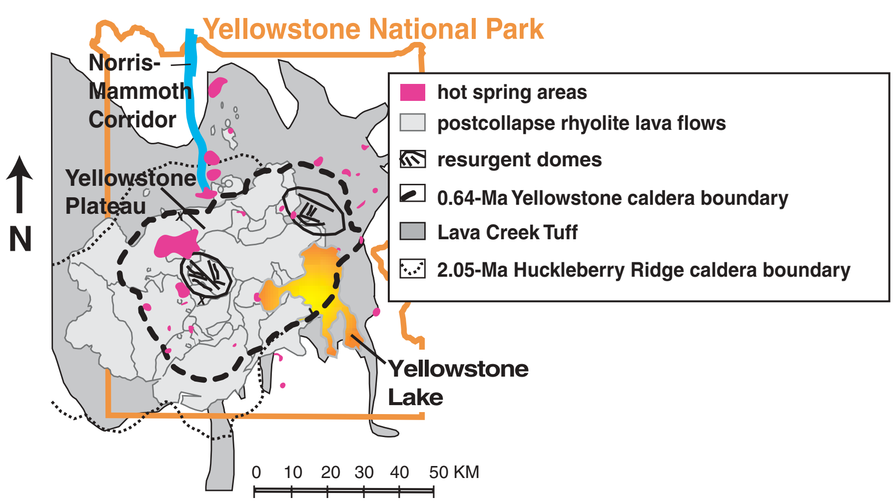
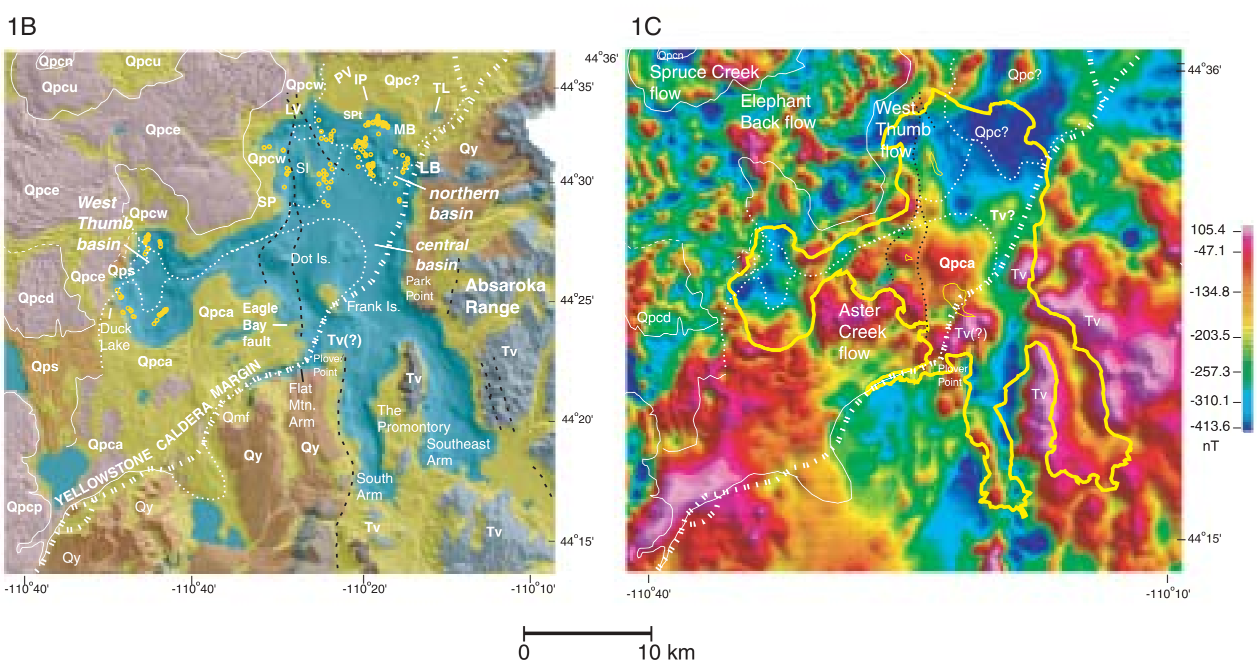


Figure 1. (A) Index map showing the 0.64-Ma Yellowstone caldera, the distribution of its erupted ignimbrite (the Lava Creek Tuff, medium gray), post-caldera rhyolitic lava flows (light gray), subaerial hydrothermal areas (red), and the two resurgent domes (shown as ovals with faults). The inferred margin of the 2.05-Ma Huckleberry Ridge caldera is also shown. (B) (facing page) Geologic shaded relief map of the area surrounding Yellowstone Lake. Yellow markers in West Thumb basin and the northern basin are locations of active or inactive hydrothermal vents mapped by seismic reflection and multibeam sonar. (C) (facing page) Color shaded-relief image of high-resolution, reduced-to-the-pole aeromagnetic map. Sources of the magnetic anomalies are shallow and include the post-caldera rhyolite lava flows (some outlined in white) that have partly filled in the Yellowstone caldera. Rhyolitic lava flows (outlined in white) underlying Yellowstone Lake are shown clearly in this map.

Glossary of terms

amphipods: crustaceans of small size and laterally-compressed body
anastomozing: joining of the parts of branched systems
bathymetric: relating to the measurement of depth and floor contour of bodies of water
breccia: sharp fragments of rock embedded in a fine-grained matrix (as sand or clay)
brittle-ductile transition zone: area where brittle and malleable rock meet beneath the earth's surface
dB: decibel
diatomaceous: consisting of or abounding in diatoms (unicellular or colonial algae having silicified cell walls)
en echelon: referring to an overlapped or staggered arrangement of geologic features
fathometer: tool used to measure fathoms (6-foot units used to measure water depth)
graben: a depressed segment of the earth's crust bounded on at least two sides by faults and generally longer than it is wide
H_2S: hydrogen sulfide
ka: thousand years ago
lacustrine: of, relating to, formed, or growing in lakes
laminated: composed of layers of firmly united material
lobate: having lobes
Ma: million years ago
mW/m^2: milliWatt per square meter
potamodromous: migratory in fresh water
reduced-to-the-pole map: aeromagnetic map designed to account for the inclination of Earth's magnetic field. Principal effect is to shift magnetic anomalies to positions directly above their sources.
seismic reflection profile: a continuous record of sound waves reflected by a density interface
silicic: of, related to, or derived from silica or silicon
strike-slip displacement: displacement whose direction of movement is parallel to the direction of its associated fault
U-series disequilibrium dating: a method of determining the age of a desposit by analyzing the isotopes produced by radioactive decay of uranium isotopes

Most definitions from Webster's Third New International Dictionary (1981)



days over a 4-year period, compared to Hayden's survey of 24 days in 1871. It began in 1999 with mapping the northern basin and continued in 2000 in West Thumb basin, in 2001 in the central basin, and in 2002 in the southern lake including the Flat Mountain, South, and Southeast Arms (see Plate 1E). Unlike any of the previous mapping efforts, the 1999-2002 swath multi-beam survey produced continuous overlapping coverage, collecting more than 220,000,000 soundings and producing high-resolution bathymetric images. Seismic reflection records of the upper 25 m of the lake bottom were obtained along with the bathymetry in the entire lake excluding the South and Southeast Arms. This effort has produced a map that is accurate to the <1-m scale in most areas. The following report focuses on results of this mapping effort and the interpretation of the newly discovered features.

Geologic setting

Powerful geologic processes in Yellowstone National Park have contributed to the unusual shape of Yellowstone Lake, which straddles the southeast margin of the Yellowstone caldera (Figure 1A), one of the world's largest active silicic volcanoes. Volcanic forces contributing to the lake's form include the explosive, caldera-forming, 2.05-Ma eruption of the Huckleberry Ridge Tuff, followed by eruption of the 0.64-Ma Lava Creek Tuff. Following explosive, pyroclastic-dominated activity, large-volume rhyolitic lava flows were emplaced along the caldera margin, infilling much of the caldera (Figures 1A, B). A smaller caldera-forming event about 140 ka, comparable in size to Crater Lake, Oregon, created the West Thumb basin. Several significant glacial advances and recessions continued to shape the lake and overlapped the volcanic events. Glacial scour deepened the central basin of the lake and the faulted South and Southeast Arms (Figure 1B). More recent dynamic processes shaping Yellowstone Lake include currently active fault systems, development of a series of postglacial shoreline terraces, and postglacial (<12-15 ka) hydrothermal-explosion events, which created the Mary Bay crater complex and other craters.

The objective of the present work is to understand the geologic processes that shape the lake floor. Our three-pronged approach to mapping the floor of Yellowstone Lake located, imaged, and sampled bottom features such as sublacustrine hot-spring vents and fluids, hydrothermal deposits, hydrothermal-explosion craters, rock outcrops, glacial features, slump blocks, faults, fissures, and submerged shorelines.

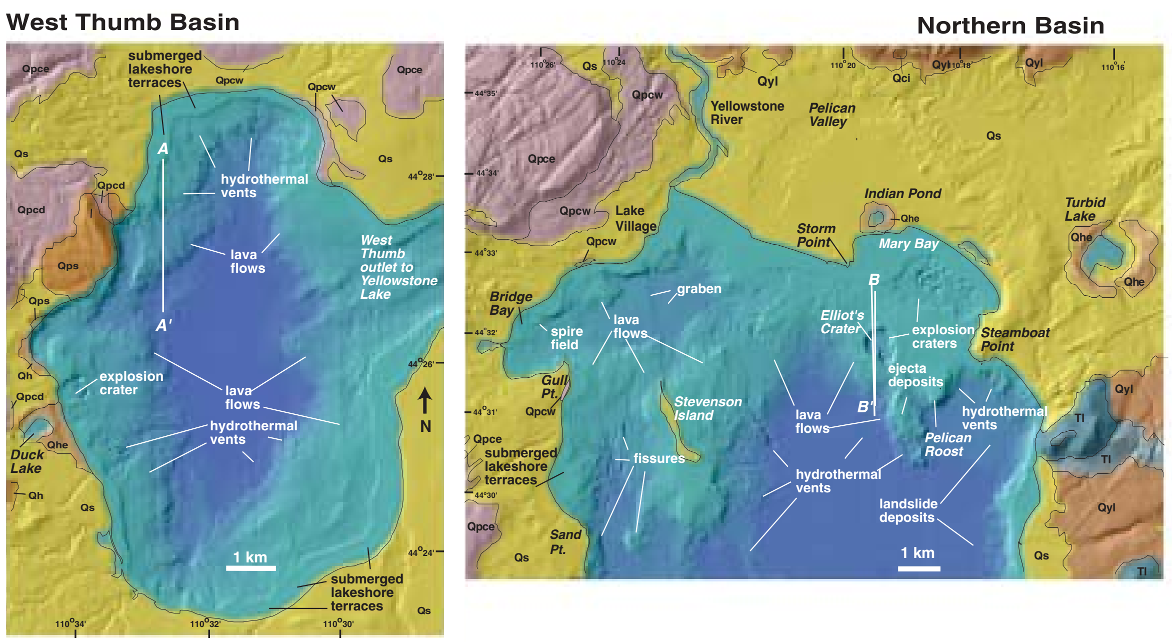


Figure 2. (A) New high-resolution bathymetric map of the West Thumb basin of Yellowstone Lake, acquired by multibeam sonar imaging and seismic mapping in 2000, showing a previously unknown ~500-m-wide hydrothermal explosion crater (east of Duck Lake), numerous hydrothermal vents, submerged lakeshore terraces, and inferred rhyolitic lava flows that underlie 7- to 10-m of post-glacial sediments. (B) High-resolution bathymetric map of the northern basin of Yellowstone Lake, acquired in 1999, showing large hydrothermal explosion craters in Mary Bay and south-southeast of Storm Point, numerous smaller craters related to hydrothermal vents, and landslide deposits along the eastern margin of the lake near the caldera margin. Post-caldera rhyolitic lava flows underlie much of the northern basin. Fissures west of Stevenson Island and the graben north of it may be related to the young Eagle Bay fault (see Fig. 1B).

Results and Discoveries of High-Resolution Mapping

Topographic margin of the caldera.

Geologic maps show the topographic margin of the Yellowstone caldera as running below lake level in Yellowstone Lake between the western entrance to Flat

Central Basin

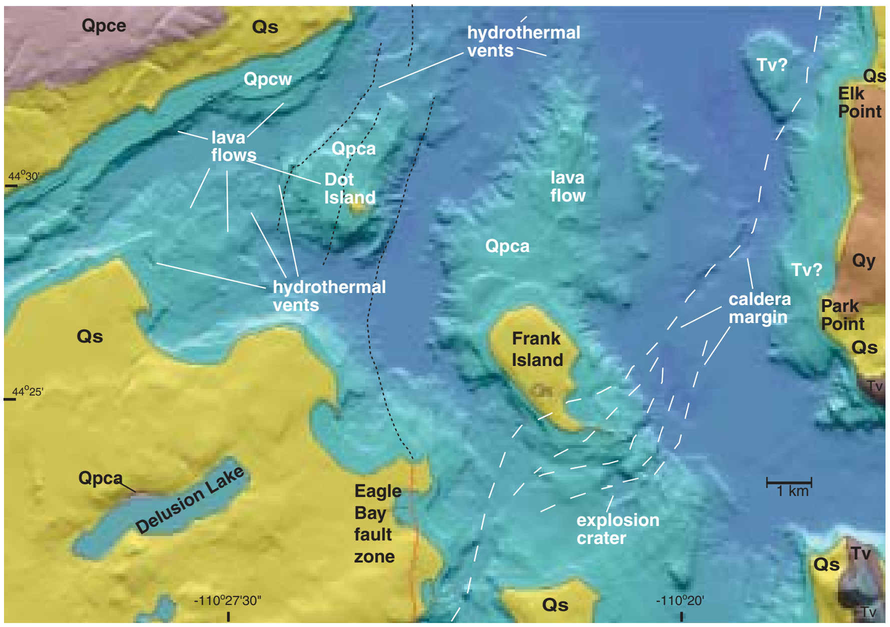


Figure 2C. High-resolution bathymetric map of the central lake basin, acquired by multibeam sonar imaging and seismic mapping in 2001, showing the Yellowstone caldera topographic margin, a large hydrothermal explosion crater south of Frank Island, and numerous faults, fissures, and hydrothermal vents as indicated.

Mountain Arm and north of Lake Butte (Figure 1B). Our mapping of the central basin of Yellowstone Lake in 2001 identified the topographic margin of the Yellowstone caldera as a series of elongated troughs northeast from Frank Island across the deep basin of the lake. Based on our new data and high-resolution aeromagnetic data, we infer the topographic margin of the Yellowstone caldera to pass through the southern part of Frank Island.

Rhyolitic lava flows.

Large-volume, subaerial rhyolitic lava flows on the Yellowstone Plateau control much of the local topography and hydrology. Characteristic lava-flow morphologies include near-vertical margins (some as high as 700 m), rubbly flow carapaces, hummocky or ridged tops, and strongly jointed interiors. Stream drainages tend to occur along flow boundaries, rather than within flow interiors.

A major discovery of the lake surveys is the presence of previously unrecognized rhyolitic lava flows underlying much of the lake floor. Field examination of rhyolite flows shows that many areas identified through the aeromagnetic mapping as having low magnetic intensity values correspond to areas with hydrothermal activity, or faulting or fracturing along which hydrothermal alteration has occurred. We believe the lava flows are key to controlling many morphologic and hydrothermal features in the lake.

Areas of the lake bottom around the perimeter of West Thumb basin (Figures 2A, 2B) have steep, nearly vertical margins, bulbous edges, and irregular hummocky surfaces, similar to postcollapse rhyolitic lava flows of the Yellowstone Plateau. Seismic reflection profiles in the near-shore areas of West Thumb basin show high-amplitude reflectors (indicating low magnetic intensity) beneath about 7–10 m of layered lacustrine sediments (Figure 3A).

Areas such as the West Thumb and Potts geyser basins in West Thumb basin, and Mary Bay in the northern basin, currently have extremely high heat flow values (1650–15,600 mW/m^2). Current heat flow values in Bridge Bay (580 mW/m^2) are relatively low compared to Mary Bay,

South, Southeast, and Flat Mountain Arms

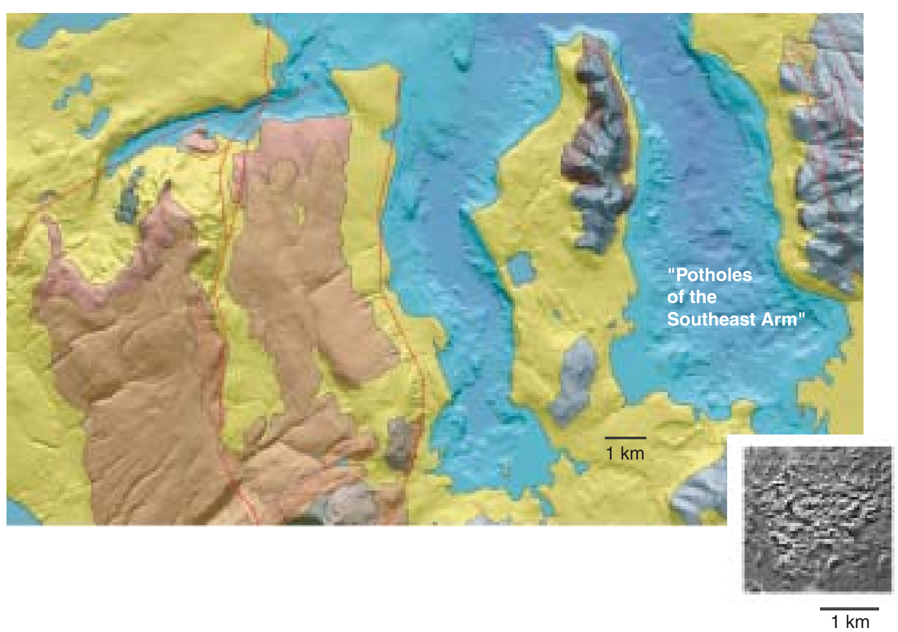
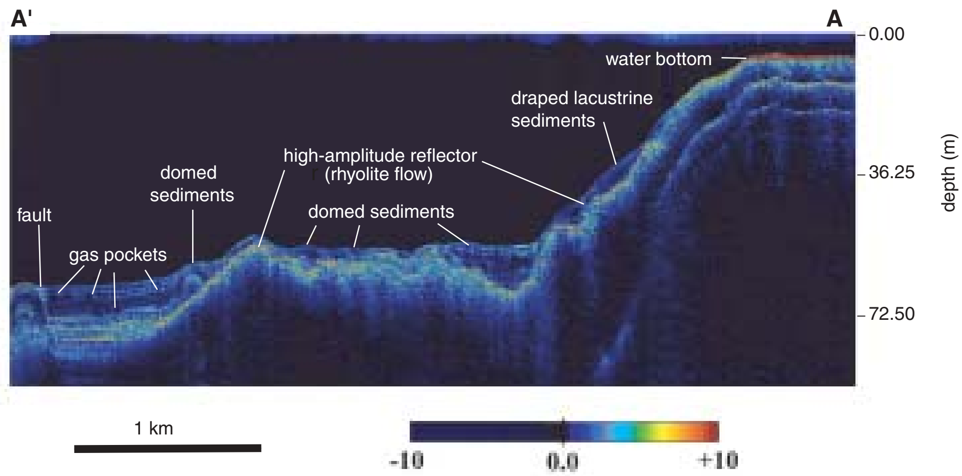


Figure 2D. High-resolution bathymetric map of the South, Southeast, and Flat Mountain Arms, acquired by multibeam sonar imaging in 2002, showing the glaciated landscape of the lake floor in the southernmost part of Yellowstone Lake and several faults. The bathymetry in the Southeast Arm contains many glacial meltwater and stagnant ice block features; the area is informally referred to as the "Potholes of the Southeast Arm," and resembles much of the kettle dominated topography mapped by Ken Pierce and others in Jackson Hole (inset image).

3A



3B

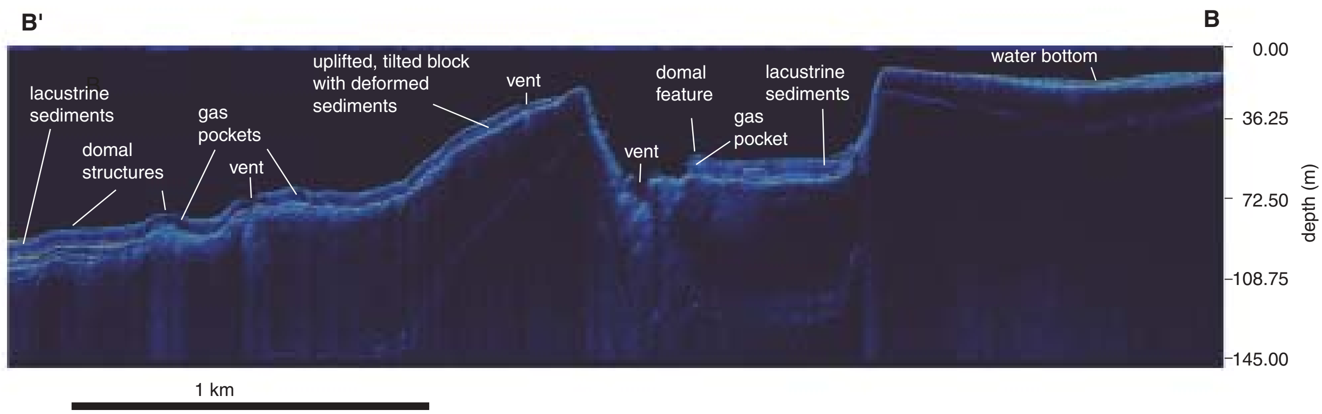


Figure 3. (A) High-resolution seismic reflection image from northwestern West Thumb basin showing high-amplitude (red) reflector interpreted as a sub-bottom rhyolitic lava flow. Glacial and lacustrine sediments, marked in blue, overlie this unit. (B) High-resolution seismic reflection image across part of Elliott's explosion crater, showing small vents, gas pockets, and domed sediments in the lacustrine sediments that overlie the crater flank. Lacustrine sediment thickness in the main crater indicates 5-7 thousand years of deposition since the main explosion. More recent explosions in the southern part of the large crater ejected post-crater lacustrine sediments and created new, smaller craters and a possible hydrothermal siliceous spire.

yet the Bridge Bay area has low magnetic intensity values. Evidence for past hydrothermal activity is present as inactive hydrothermal vents and structures, and may have been responsible for demagnetization of the rocks there. South of Bridge Bay and west of Stevenson Island, low magnetic intensity values reflect active hydrothermal venting and relatively high heat flow values. Low magnetic intensity values in the northern West Thumb basin also may be due to past hydrothermal activity, as evidenced by vent structures there. Comparison of geologic maps (Figure 1B) with the high-resolution aeromagnetic maps shows a crude relation of magnetic anomalies to the mapped individual lava flows on land (Figure 1C).

The magnetic signatures, combined with the high-resolution bathymetric and seismic reflection data, allow identification and correlation of sediment-covered rhyolitic lava flows far out into the lake (Figures 1, 2). For example, the Aster Creek flow (Qpca) southwest of the lake (Figure 1C) is associated with a consistent, moderately positive, magnetic anomaly that extends over the lake in the southeast quadrant of West Thumb basin, along the southern half of the West Thumb channelway, and over the central basin of the lake well past Dot and Frank Islands (Figures 1, 2). The Aster Creek flow has few mapped faults, and few areas that have been hydrothermally-altered. Similarly, the West Thumb flow (Qpcw) can be traced into the lake in northeastern West Thumb basin, along the northern half of West Thumb channelway, and into the northern basin beneath Stevenson Island and Bridge Bay (Figure 2C). In contrast, the Elephant Back flow contains a well-developed system of northeast-trending faults or fissures that has been extensively altered so that the magnetic signature of this unit is fractured with a wide range of values in magnetic intensity (Figure 2D).

Field examination of subaerial rhyolitic lava flows indicates that negative magnetic anomalies, for the most part, are associated with extensive hydrothermal